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DOI:
10.1680/esu.14.00010

Engineering Sustainability
Volume 167 Issue ES6

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ice | **proceedings**

Proceedings of the Institution of Civil Engineers
Engineering Sustainability 167 December 2014 Issue ES6
Pages 249–263 http://dx.doi.org/10.1680/esu.14.00010
Paper 1400010
Received 19/03/2014 Accepted 30/09/2014
Keywords: infrastructure planning/renewable energy/risk & probability analysis

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Institution of Civil Engineers
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Supergrid: projecting interconnection capacities for the UK

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Interconnected electricity networks, supergrids, are being considered in Europe as a way to help tackle two current global challenges – rapidly increasing energy demands and rising carbon dioxide emissions. As with any new approach, there is a range of risks associated with developing interconnections, not least the availability of surplus electricity for exportation between various candidate countries. While the future is never certain, the process of generating a range of possible capacities for these interconnections should be considered as a necessary precursor for mitigating risks within decision-making processes. In facilitating this objective, this paper proposes a step-wise methodological framework for assessing the probabilities of achieving surplus capacity provision within a UK pan-European supergrid. This includes application of a newly developed tool for proposing a range of energy supply/demand scenarios in conjunction with the @Risk assessment tool. Through example scenarios it is shown how P80 (80th percentile) interconnection capacities for 2030 can be assessed. The results suggest that, of the nine candidate countries, Germany could provide the greatest (10·97 GW) surplus capacity with an 80% chance. It is concluded that, with further stakeholder engagement, the developed framework will provide a deeper understanding of the key fundamental risks associated with interconnections as well as mitigation measures.

Notation

D_p	peak demand (GW)
E_a	available capacity (GW)
E_e	export capacity (GW)
E_s	surplus capacity (GW)
F_1	total renewables intermittency load factor
F_2	exportation quota

1. Introduction

Developed and developing nations face two major global issues, both now and in the future – growing energy demands and rapid climatic changes. Sustainability is a broad theme that requires cognisance of economic, social and environmental aspects. In its broadest sense it is about ensuring that we do not severely impact the ability of future generations to meet their needs as we endeavour to meet our own (Brundtland, 1987; De-Shalit, 1995; Reiter, 2013). Most of what is done today within a well-functioning modern society (and its supporting economy) is impacted in one way or another by the thirst for energy. Unfortunately, when sourced from fossil fuels, it is to the detriment of the environment. Anthropogenic concentrations of carbon dioxide in the atmosphere have been increasing over the past century (the June 2014 concentration (401 ppm) was about 43% higher than that in the mid-1800s (OECD/IEA, 2012; Tans and Keeling, 2014)) and there is consensus among scientists that this is linked directly to a warming climate.

Electric power industries are undeniably major producers of the world's greenhouse gas (GHG) emissions (Moselle *et al.*, 2012). Continually growing global energy demands and the combustion of fossil fuels has undoubtedly been a major source of carbon dioxide in the atmosphere, and this demand for energy is projected to increase by one-third between 2010 and 2035 (OECD/IEA, 2011). This is due in no small part to global rates of population growth allied with substantial economic development in new emerging markets (Yusaf *et al.*, 2013) such as China and India. This has resounding implications for the sustainability agenda at local, national and international scales where carbon dioxide emissions (and their measurement) are so well intertwined.

In response to these challenges, a requirement to replace fossil fuel power plants with 'low carbon dioxide' and renewable resources now appears to form a linking thread through European energy policy. For example, the European Commission (2007) agreed a set of binding legislation measures that aims to reduce GHG emissions by 20% (from 1990 levels) by 2020. This requires that the share of European Union (EU) renewable resources increases to 20%. In fulfilling this aim, the concept of the 'supergrid' has been conceived and developed to assimilate interconnected European renewable energy sources into a pan-European grid. The 'supergrid' integrates high-voltage direct current (DC) networks into existing low and high-voltage alternating current (AC) networks. In December 2010, a 'memorandum of understanding' was signed by ten European states including the UK, making possible the transfer of renewable energy from northern marine and southern solar resources to European centres of population (ECCC, 2011a). In 2011, the UK Energy and Climate Change Committee (ECCC) subsequently launched an inquiry to investigate the potential for building a European supergrid (ECCC, 2011a). In the first quarter of 2014, the UK generated 19·4% of its electricity from renewable sources, with a 2·7 GW increase in installed capacities throughout 2013 (DECC, 2014). In the same period, the UK was a net importer of electricity from interconnections with France (3·6 TWh) and the Netherlands (2·0 TWh) (DECC, 2014).

Governments, policy makers and private investors would seek to adopt a cost-effective, secure and 'low-risk' approach when considering developing interconnections of renewable energy between EU member states and the UK. Ultimately, this requires decisions to be made concerning the best countries for the UK to 'interconnect' with and share energy (ECCC, 2011b). To facilitate this process, this paper briefly reviews the literature (Section 2) before proposing an innovative methodological approach to interconnections (Section 3) using a newly developed (Excel-based) scenarios tool in conjunction with the @Risk package (Palisade Corporation, 2012). To elucidate this methodology further, some carefully selected examples are provided and the results are presented. The wider implications for the adoption of supergrid interconnections are subsequently discussed in Section 4 and conclusions are drawn in Section 5.

2. Literature review

2.1 Uncertainty in energy projections

A variety of methods have been adopted around the globe by many researchers to analyse future energy supply/demand and model associated risks (where definition and probabilistic assignment can be achieved) and uncertainties (where description without probabilistic assignment can be achieved). For instance, more than 40 years ago Salter (1973) described a probabilistic forecasting methodology in which stochastic data and subjective probability estimates were used to achieve a probabilistically stated forecast at a future time frame (the year 2000) for electricity consumption of the USA. The probabilistic (rather than deterministic) approach allowed for quantification of relative risks associated with alternative energy strategies to be highlighted, which could then be converted to planning decisions. More recently, similar analyses have been used to allocate probabilities to uncertainty regarding future temperature(s) and their impact on energy supply and demand in the USA when implementing cryogenic carbon dioxide capture (Hamlet *et al.*, 2010).

In contrast, researchers in the UK have identified risks and uncertainties associated with four different future scenarios (i.e. low carbon dioxide, low carbon dioxide resilient, reference and resilient), adopting analytical tools (Markal, Wasp and CGEN) in order to build a resilient UK energy system (Chaudry *et al.*, 2011). Probabilities were not attached to energy scenarios, but a methodology for implementing such a procedure was described in detail by Morgan and Keith (2008: p. 196).

With respect to interconnections, various deterministic techniques and methods for calculating interconnection capacities are being introduced and adopted (e.g. Denny *et al.*, 2010; Georgiou *et al.*, 2011). However, literature on the risks and uncertainties of interconnections is less well developed. While economists such as Parail (2010) have introduced a probabilistic methodology to add economic uncertainty to electricity trading by way of interconnections, this has not been extended to uncertainties associated with generating surplus electricity. The methodology introduced in Section 3 provides a broader capacity assessment for interconnections by addressing this shortfall through focusing on a probabilistic approach for estimating surplus electricity.

2.2 Risk management and its implication for interconnections

Minimising the risks associated with construction and maintenance of a project requires understanding of their causes, consequences and probabilities of occurrence (BSI, 2010). Thus, when selecting the best country for the UK to interconnect with, three stages of risk assessments should typically be applied

- risk identification
- risk semi-quantification
- risk quantification.

The initial but vital stage of risk identification should highlight uncertainties related to projecting interconnection capacities. The approach adopted within this paper provides a robust framework for risk assessors to move past single-point estimation in order to understand better the possibilities for supply and demand that might occur. Other uncertainties will be directly related to, or influenced by, project complexity, construction time (10 years for some seabed interconnections), duration of asset use (40 years or more), inaccuracies in cost estimation (see Flyvbjerg *et al.*, 2003) and the involvement of various disciplines and stakeholders. (Early-stage risk assessment can significantly reduce the cost of projects by restricting unnecessary spend, especially of the contingencies allocated for cost uncertainty (IRG, 2013).) Allied to this, an interconnection project is notoriously risky because two countries are involved, each with their own policies. In the past, these risks have led to European projects being put on hold for decades (e.g. France–Spain and UK–Norway).

When considering quantitative and semi-quantitative risk assessment, the main challenge for interconnections is data collection, both for assessing the impact and probability of risks. This is paramount as construction projects are very often one-off enterprises (Flanagan and Norman, 1993). To overcome this challenge, individual knowledge, experience, judgement and rules of thumb should be structured to facilitate risk assessment (Dikmen *et al.*, 2007). In financial decision-making processes and techniques, a 'single' value is required with a desired achievement possibility assigned. While risk assessment can be used to generate a single value from a range of possible final capacities, it requires characteristically subjective judgement without standardisation (IRG, 2013).

The theoretical framework presented in this paper goes a significant way towards filling this gap in knowledge by allowing risk assessment to be undertaken in the appraisal stage of a project. This is a significant step towards assessing the best country that the UK should interconnect with (and thus also identifying the least suitable partner countries).

3. Methodology

The three-step methodology is

- step 1 – scenario generation (Section 3.1)
- step 2 – assessment of interconnection capacities (Section 3.2)
- step 3 – risk assessment (Section 3.3).

3.1 Step 1: Scenario generation

In this step (informed by future projection scenarios) it was necessary to generate a range of capacities for supply/demand. When considering two interconnected countries, this then allows calculation of 'spare' electricity capacity that can be traded in either direction (step 2). Three sub-steps were required.

3.1.1 Step 1a: Developing an Excel-based scenario tool

There is a plethora of electricity supply mixes and/or energy demand projections, hence complicated decision-making procedures require in-depth consideration of the various scenarios that are being developed. This requires a high level of knowledge that is available only within a team of experts that are well versed on the various techniques of future scenarios analysis. Alternatively, what is missing is a tool that acts as a database for existing energy supply/demand scenarios and allows the user to look up existing scenarios or mix and match existing scenarios for a country, leading to a range of new possibilities and to allow alternative approaches to be considered. Such a tool has been developed by Torbaghan *et al.* (2013), the salient features of which are described therein. To summarise, around 50 studies are incorporated within the database of the tool, each of which provides various supply/demand projection scenarios according to a range of countries' renewable and non-renewable supply technologies (Table 1). (The criterion for selecting the nine countries for interconnection with the UK was distance, this being the major influential parameter on capital costs.) As an example, and to show the breadth of information used within this study, the offshore wind technology scenarios for the UK are presented in Figure 1.

3.1.2 Step 1b: Ranking technologies

All the technologies were assessed in terms of their lifecycle emissions and load factors (i.e. likely availability due to external conditions such as wind, sunshine, water flow rates and so on). Multiplying lifecycle emissions by the load factor leads to a pollution factor by which the technologies can be ranked from the most emitting (12) to least emitting (1), as shown in Table 2 (see Torbaghan *et al.* (2013) for more details). It should be noted that, for the purposes of this study, carbon dioxide capture and storage (CCS) is not considered a renewable technology as it requires fossil fuel for its implementation.

3.1.3 Step 1c: Development of extreme scenarios

Based on these data, the tool is subsequently used (here) to develop two differently themed scenario sets – renewable scenarios and fossil fuel scenarios. Due to the fact that historical data show that at least 10 years are required for the design and implementation of interconnections (Strbac *et al.* (2013) report an average of 5 years for construction and 5 years is assumed for pre-study and design), the year 2030 was selected.

3.1.3.1 RENEWABLE SCENARIOS

This scenario set seeks to 'maximise the use of renewable energy in order to reduce carbon dioxide emissions while minimising reliance on fossil fuels'. Using this ethos, ten individual scenarios were developed (i.e. one for the UK and one for each of the nine European countries considered). These scenarios were developed assuming that energy supplies therein are sourced from the available renewable technologies of each country (i.e. those ranked 1 are adopted first, followed by those ranked 2 and so on). The share of each supply technology for each country from 2010 to 2030 is presented in Figure 2. For clarity, the final breakdown of supplies for 2030, which will be used in step 2, is presented in Figure 3(a).

3.1.3.2 FOSSIL FUEL SCENARIOS

This scenario set seeks to 'maximise the share of fossil fuels and minimise renewable sources, increasing reliance on fossil fuels'. Using this ethos, ten individual scenarios were developed (one for the UK and one for each of the nine European countries).

Technology	UK	Sweden	Spain	Norway	Netherlands	Ireland	Germany	France	Denmark	Belgium
Marine	20 [1–9]	3 [5]	6 [5, 10, 11]	3 [5]	8 [5, 10, 11]	8 [5, 10–13]	—	6 [5, 10, 11]	5 [5, 10, 11]	—
Offshore wind	26 [1–4, 6, 9, 14–17]	—	—	—	6 [18, 19]	3 [12, 13, 20]	4 [21]	—	—	—
Onshore wind	14 [1, 2, 6, 9, 15, 16]	—	—	—	9 [5, 10, 11, 18, 19, 22]	8 [10–13, 20, 22]	9 [5, 11, 21]	—	11 [5, 10, 11, 18, 22–24]	11 [5, 10, 11, 25, 26]
Wind	—	12 [5, 10, 11, 23, 27]	7 [5, 10, 11, 18, 28]	11 [5, 11, 23, 27]	—	—	—	7 [5, 10, 11, 18, 22]	—	—
Hydro	22 [1, 4–9, 16, 29]	7 [5, 10, 11, 27]	7 [5, 10, 11, 28]	8 [5, 11, 27]	6 [5, 10, 11, 19, 22]	6 [5, 10, 11, 13, 20, 22]	8 [5, 11, 21]	6 [5, 10, 11]	6 [5, 10, 11]	5 [5, 10, 11]
Pumped storage	8 [1, 4, 6, 7, 30]	—	—	—	—	1 [20]	2 [21]	—	—	—
Biomass	15 [1, 2, 5, 6, 9, 29]	10 [5, 10, 11, 27]	9 [5, 10, 11, 28]	5 [5, 11, 27]	9 [5, 10, 11, 19, 22]	7 [5, 10, 11, 13, 20, 22]	9 [5, 11, 21]	7 [5, 10, 11]	7 [5, 10, 11]	9 [5, 10, 11, 25]
Solar (PV)	—	7 [5, 10, 11]	9 [5, 10, 11, 28]	—	9 [5, 10, 11, 19, 22]	6 [5, 10, 11, 20, 22]	9 [5, 11, 21]	7 [5, 10, 11]	7 [5, 10, 11]	10 [5, 10, 11, 25]
Geothermal	—	—	6 [5, 10, 11]	—	—	—	7 [5, 11, 21]	6 [5, 10, 11]	—	—
Nuclear	37 [1, 2, 4–9, 16, 29–32]	9 [5, 10, 11, 27, 33]	10 [5, 10, 11, 28, 33]	—	10 [5, 10, 11, 19, 33]	5 [5, 10, 11, 20]	8 [5, 11, 21, 27]	7 [5, 10, 11, 33]	2 [10, 11]	9 [5, 10, 11, 25, 33, 34]
Gas	28 [1, 2, 4–8, 29, 30]	10 [5, 10, 11, 27]	9 [5, 10, 11, 28]	—	8 [5, 10, 11, 19]	8 [5, 10, 11, 13, 20]	9 [5, 11, 21, 27]	6 [5, 10, 11]	6 [5, 10, 11]	8 [5, 10, 11, 34]
Gas + CCS	17 [2, 4, 6–9, 16]	—	—	—	—	—	—	—	—	—
CHP	5 [2, 6, 29]	—	—	—	—	—	—	—	—	1 [34]
Coal	21 [1, 2, 4–8, 29, 30, 32]	—	8 [5, 10, 11, 28]	—	5 [5, 11]	4 [5, 11]	10 [5, 11]	6 [5, 10, 11]	6 [5, 10, 11]	9 [5, 10, 11, 34]
Coal + CCS	23 [2, 4, 6–9, 29, 30]	—	—	—	—	—	—	—	—	—
Oil	11 [1, 4, 6–8, 30]	—	4 [10, 28]	—	—	2 [10, 20]	—	2 [10]	2 [10]	3 [10, 25]
Other fossil fuels	—	2 [10]	—	—	—	—	—	—	—	—

[1]National Grid (2012), [2]Poyry (2010), [3]Esteban *et al.* (2011), [4]UKERC (2009), [5]Energynautics GmbH (2011), [6]Barnacle *et al.* (2012), [7]Chaudry *et al.* (2011), [8]Dagoumas and Barker (2010), [9]Mott MacDonald (2011), [10]Capros *et al.* (2010), [11]Greenpeace (2011), [12]IMERC (2011), [13]Argyropoulos and Gardner (2012), [14]Hawkins *et al.* (2011), [15]National Grid (2011), [16]Butler *et al.* (2012), [17]Decker *et al.* (2011), [18]EWEA (2011), [19]Greenpeace (2013), [20]EIRGRID (2013), [21]Lindberg (2013), [22]ECN (2011), [23]Juul and Meibom (2012), [24]Olesen (2010), [25]D'haeseleer *et al.* (2007), [26]Gill (2013), [27]Wiuff *et al.* (2007), [28]López-Peña *et al.* (2011), [29]Grubb *et al.* (2006), [30]DECC (2011b), [31]WNA (2012), [32]ENSG (2012), [33]WNA (2013), [34]Geldhof and Delahaije (2013)

Table 1. List of technologies, candidate countries and sources of information (Number in Bold highlights scenarios available currently within database)

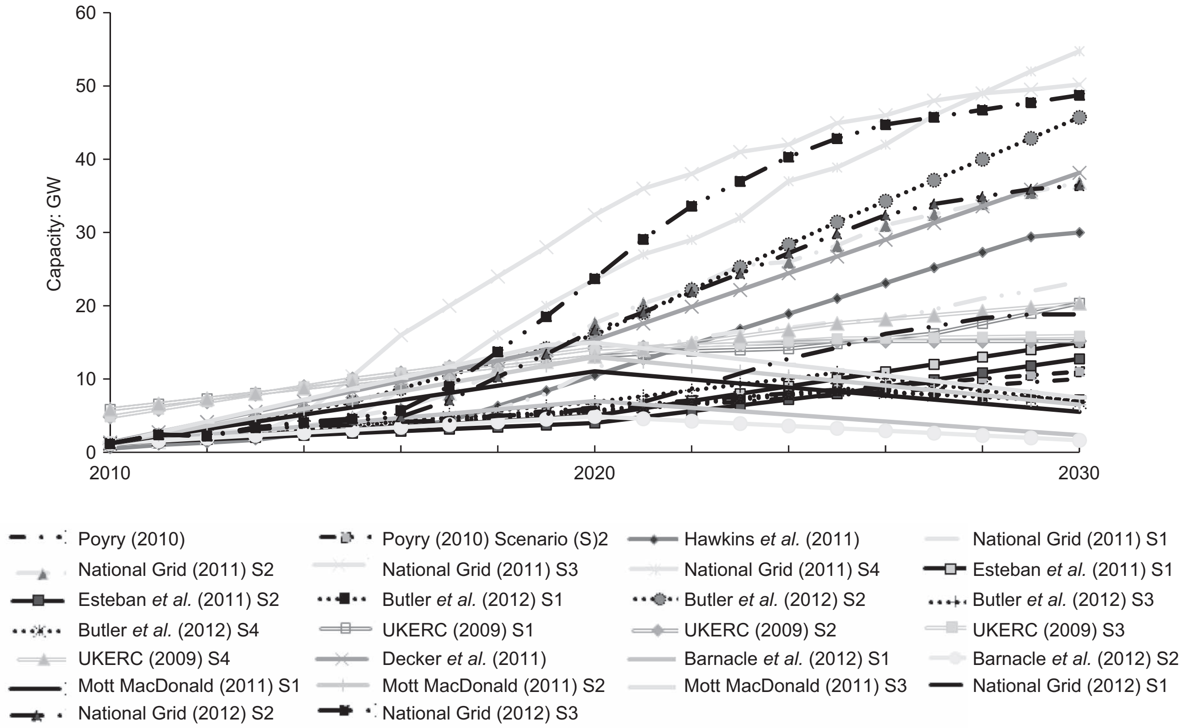

Figure 1. Offshore wind technology scenarios for the UK up to 2030

	Lifecycle emissions: tCO_2e/GWh	Load factor: %	Pollution factor ($A \times B$)	Ranking
Technology	*A*	*B*	*C*	*D*
Onshore wind	9·5	30	3	1
Offshore wind	9·5	30	3	1
Pumped storage	36	15	5	2
Marine	20	25	5	2
Solar (PV)	17	30	17	3
Biomass	48	53	26	4
Hydro	86	40	34	5
Nuclear	57	90	51	6
Gas + CCS	110	90	99	7
Coal + CCS	118	90	106	8
Combined heat and power	474	92	436	9
Oil	771	90	694	10
Gas	1100	90	990	11
Coal	1180	90	1062	12

Table 2. Technological influences for scenario development Torbaghan *et al.* (2013)

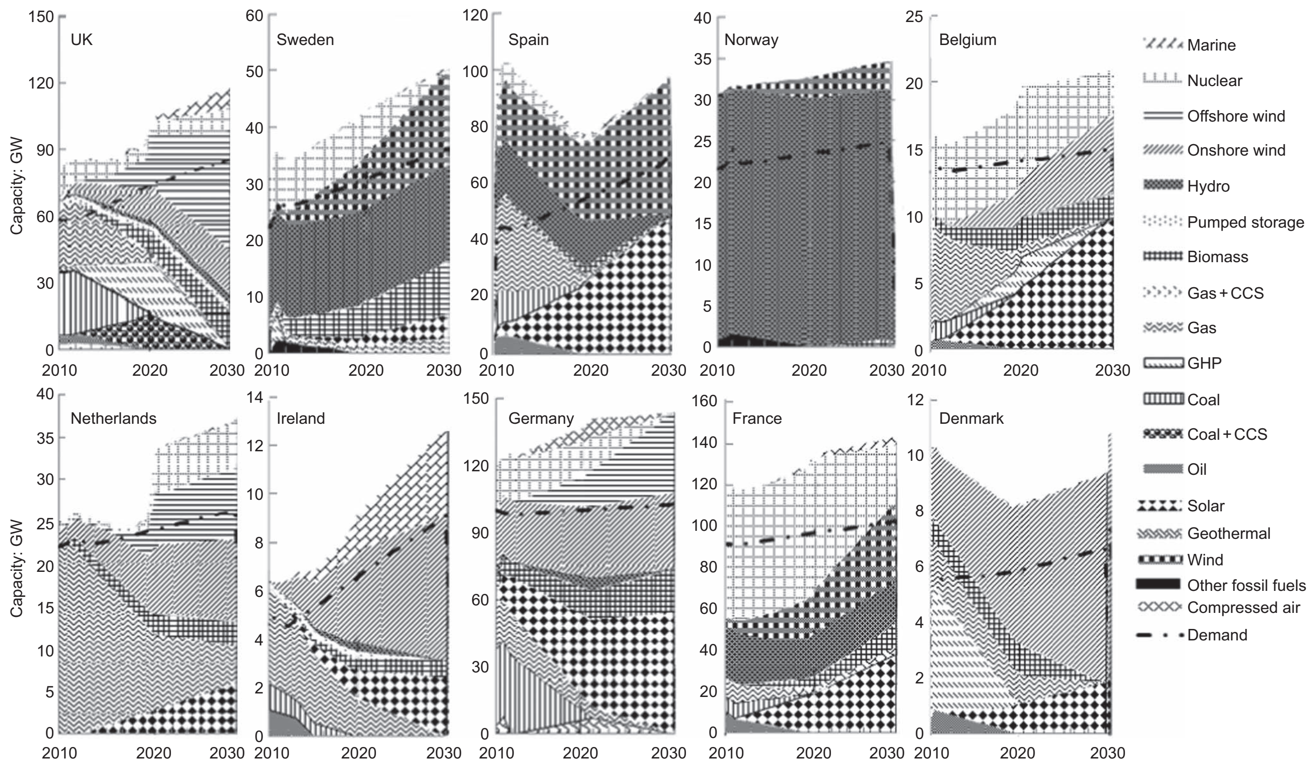

Figure 2. Share of supply by technology and country (renewable scenarios 2010 to 2030)

These scenarios were developed assuming that energy supplies therein are sourced from the available non-renewable technologies of each country (i.e. those ranked 12 are adopted first, followed by those ranked 11 and so on). The final breakdown of supplies is presented in Figure 3(b). Each scenario set will always draw from a narrative and a set of assumptions (Boyko *et al.*, 2012; Hunt *et al.*, 2012). For example, two general common assumptions (factors) for generating the scenarios adopted in this paper are economic growth and taxation on carbon dioxide emissions or meeting associated emissions

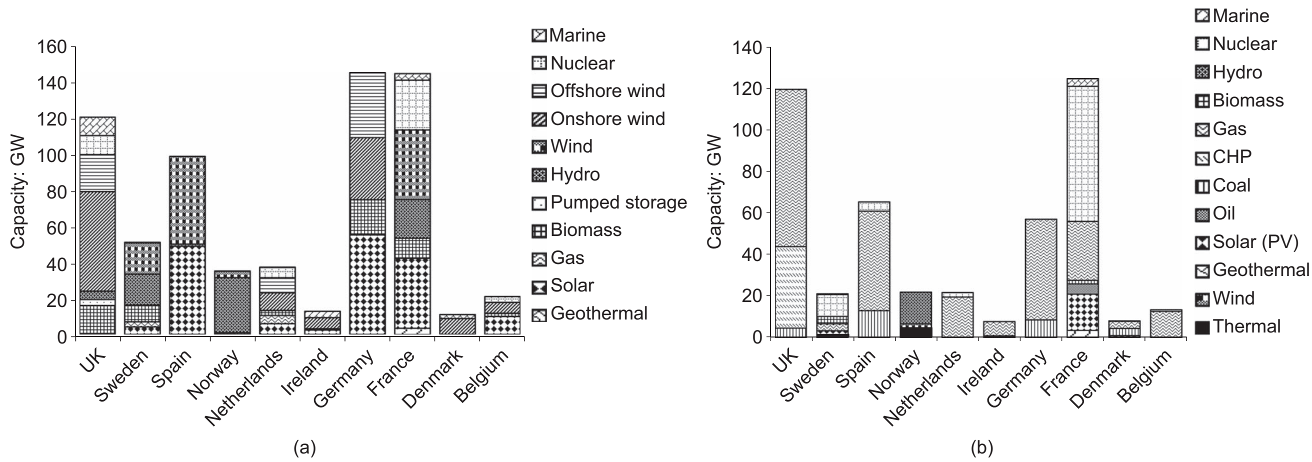

Figure 3. Share of technologies in (a) renewable scenarios and (b) fossil fuel scenarios in 2030

targets (e.g. Capros *et al.*, 2010; Greenpeace, 2011; National Grid, 2012). Both play vital roles when comparing the economic viability of renewable with fossil fuel technologies. Taking Germany as an example, the narrative would state that there would be a dramatic drop in total electricity generation capacity due to selection of a lowest demand projection scenario (i.e. from 100 GW (Statistisches Bundesamt, 2013) to around 40 MW (Wiuff *et al.* (2007)) based on an assumption of medium economic growth coupled with a strong focus on improved energy efficiency measures, driven by Germany's policy to go non-nuclear by 2022.

3.2 Step 2: Assessing interconnection capacities

This step estimates the capacity of surplus energy and exported energy for interconnection across both candidate and target countries (in this case the UK). This requires the following two sub-steps.

3.2.1 Step 2a: Calculate 'surplus' capacity

The surplus capacities for the UK and candidate countries can be calculated according to

1. $$E_s = E_a - D_p$$

in which E_s is surplus capacity, E_a is available capacity and D_p is peak demand.

In the example presented here it is assumed within the newly developed renewable scenario set and fossil fuel scenario set that in 2030 (the reasoning behind which is not known and does not need to be justified) the UK seeks to connect to the supergrid to import only renewable energy. By making this dramatic assumption Equation 1 can be used to calculate $E_{s(min)}$ and $E_{s(max)}$ (i.e. available surplus capacity of renewable energy that could be drawn from each of the nine candidate countries). The minimum values are based on the ten fossil fuel scenarios while the maximum values are based on the ten renewable scenarios. Table 3 shows that the greatest value of $E_{s(max)}$ (i.e. the highest available renewable capacity supplied to the UK through the supergrid) is 41·3 GW, supplied from Germany. The minimum value is zero from all countries apart from Norway.

3.2.2 Step 2b: Calculate 'export' capacity

The surplus capacity E_s calculated in Equation 1 does not provide a true reflection of the energy that could be exported to the UK (E_e) through the supergrid. In each country this should take cognisance of intermittency and availability (exportation quota) through

2. $$E_e = E_s F_1 F_2$$

where E_e is export capacity, F_2 is the exportation quota and F_1 is the total renewables intermittency load factor, given by

3. $$F_1 = \sum_{x=1}^{n} A_x B_x / 100$$

in which A_x is the renewables intermittency load factor for a specific technology x and B_x is the contribution (in %) to $E_{s(total)}$ for technology x. For example, when using mean values (Table 3), the value of $E_{e(total)}$ for Sweden is

$$E_{e(total)} = 5{\cdot}65 \times 0{\cdot}36 \times 0{\cdot}99$$
$$= 2{\cdot}0 \text{ GW or } 17\,640 \text{ GWH/year}$$

	E_s: GW					E_e: GW (GWh/year [a])		
	Min.	Mean	Max.	$F_{1(mean)}$	F_2	Min.	Mean	Max.
UK	0	11·90	23·80	0·30	0·99	0 (0)	3·5 (30 960)	7·1 (61 921)
Sweden	0	5·65	11·30	0·36	0·99	0 (0)	2·0 (17 640)	4·0 (35 279)
Spain	0	14·00	28·00	0·30	0·99	0 (0)	4·2 (36 424)	8·3 (72 848)
Norway	1·87	5·43	8·99	0·39	0·99	0·72 (6325)	2·1 (18 366)	3·5 (30 406)
Netherlands	0	0·27	0·53	0·23	0·99	0 (0)	0·1 (529)	0·1 (1057)
Ireland	0	1·82	3·64	0·30	0·99	0 (0)	0·5 (4735)	1·1 (9470)
Germany	0	20·65	41·30	0·34	0·99	0 (0)	7·0 (60 889)	13·9 (121 778)
France	0	6·77	13·54	0·29	0·99	0 (0)	1·9 (17 027)	3·9 (34 053)
Denmark	0	1·56	3·12	0·30	0·99	0 (0)	0·5 (4059)	0·9 (8117)
Belgium	0	1·37	2·74	0·27	0·99	0 (0)	0·4 (3208)	0·7 (6416)

[a]Values in GWh/year calculated by multiplying by 8760 (24 h/d, 365 d/year)

Table 3. Projected renewable export capacity for a sample set of European countries in 2030

Ranges of projected export capacities from nine candidate countries to the UK are presented in Table 3. A three-point estimate is generated: $E_{e(max)}$ (the maximum export availability to the UK with maximum E_s), $E_{e(min)}$ (the minimum export availability to the UK with minimum E_s) and $E_{e(mean)}$ (the most likely export availability to the UK with most likely E_s). It can be seen from Table 3 that Germany and Spain have the highest export availability for 2030, with $E_{e(mean)}$ estimates of 7·0 GW and 4·2 GW, respectively. The Netherlands has the lowest value, at 0·1 GW, which is surprising as a new interconnection between the UK and the Netherlands (BritNed) was commissioned in 2011. The considered load factors F_1 for each country (based on the renewable scenarios) are presented in Table 3 with associated variables of A_x and B_x listed in Table 4. F_2 reflects a 1% chance of an unscheduled outage based on the work of Chatzivasileiadis *et al.* (2013). In this paper, unscheduled outages are assumed to be the same in all countries but the methodology allows for individual values to be assigned should they be required.

3.3 Step 3: Risk assessment

In this step a preliminary 'qualitative' risk analysis is implemented to assess the probability (thereby acknowledging uncertainty) of achieving renewable capacities for E_s and E_e, outlined previously in step 2. This is done through the Excel-based @Risk software as recommended by the Infrastructure Risk Group (IRG, 2013). This @Risk function is used to represent a range of 'possible' values that the factors could take instead of limiting them to a singular case (Palisade Corporation, 2012). The process is now described in two stages – input and output.

3.3.1 Input

In this stage, E_s, F_1 and F_2 should be defined as input variables for @Risk and a probability distribution function must be chosen to represent them. While it could be argued that the choice of probability distribution is subjective and has a considerable effect on the results (Sweeting, 2011), the major contributing factor is the type of data.

In this paper 'continuous' distributions (i.e. a simplifying triangular probability density function) for E_s are adopted bounded to minimum and maximum values. While there are various bounded distribution(s) that could have been used (e.g. pert, beta and uniform) there is a lack of historical (observed) data against which to compare. Moreover, asymmetrical non-parametric distribution(s) based on three-point estimates (widely used by industry) have been shown to be more closely aligned with triangular rather than betapert distributions due to the levels of uncertainty achieved (Hulett, 2011).

In this paper F_1 is defined as a random variable by allocating a 'general' distribution to it for each country, which reflects the uncertainties associated with adopting a mixture of renewable technologies for trading purposes (A_x) and renewable

	Hydro		Geothermal		Biomass		Wind		Solar		Pumped storage		Marine	
	A_1	B_1: %	A_2	B_2: %	A_3	B_3: %	A_4	B_4: %	A_5	B_5: %	A_6	B_6: %	A_7	B_7: %
UK	0·4	4	—	—	0·53	13	0·3	63	—	—	0·15	3	0·25	9
Sweden	0·4	34	—	—	0·53	18	0·3	34	0·3	8	—	—	0·25	1
Spain	0·4	1	—	—	—	—	0·3	49	0·3	49	—	—	—	—
Norway	0·4	87	—	—	0·53	3	0·3	10	—	—	—	—	—	—
Netherlands	—	0	—	—	0·53	7	0·3	48	0·3	16	—	—	0·25	1
Ireland	—	0	—	—	0·53	6	0·3	48	0·3	19	—	—	0·25	28
Germany	—	0	—	—	0·53	14	0·3	49	0·3	38	—	—	—	—
France	0·4	15	0·8	2	0·53	8	0·3	27	0·3	27	—	—	0·25	3
Denmark	—	0	—	—	—	—	0·3	80	0·3	20	—	—	—	—
Belgium	0·4	1	—	—	0·53	8	0·3	28	0·3	47	—	—	—	—

Table 4. Contributing factors for F_1

intermittency issues (B_x). For example, in the renewable scenario (Table 4) Norway has available electricity to export from hydro ($A_1 = 0{\cdot}4$, $B_1 = 87\%$), biomass ($A_3 = 0{\cdot}53$, $B_3 = 3\%$) and wind ($A_4 = 0{\cdot}3$, $B_4 = 10\%$), the assigned probability distributions being shown in Figure 4.

The probability associated with F_2 (1% chance of an outage due to unscheduled maintenance) is modelled using a 'binomial' distribution (riskbinomial) that specifies the number of trials and probability of success (99% in this case) of each. The number of trials is set as 1, so there are two possible outcomes (0 or 1) where 0 (outage) has a 1% probability. By setting Equation 2 as the worksheet formula, E_e becomes the output of the simulation.

3.3.2 Output

@Risk is used to recalculate values of E_s, F_1, F_2 and E_e (for each of the ten chosen countries) many thousands of times (in this case 5000). During this Monte Carlo simulation, @Risk random values for E_s, F_1 and F_2 are sampled from the assigned distribution function and placed within a statistical model; each time the resulting outcome is ultimately recorded to form a probability distribution for E_e. Figure 5 shows a risk analysis distribution for Norway in 2030. The distribution can be used to read 80th percentile (P80) capacities (i.e. an 80% probability of E_e being less than this value). The respective $E_{e(P80)}$ values for all candidate countries are summarised in Table 5, from which it can be seen that Germany has the highest value (10·97 GW) and the Netherlands has the lowest value (0·13 GW).

4. Discussion

The developed tool has huge implications for decision makers to assess interconnection capacities by generating a range of energy supply/demand scenarios. The distinct advantage is that it does not require a team of experts and can be operated on a limited budget or where time restrictions exist.

Basing a decision purely on P80 capacities, the current analysis would suggest that Germany is the best country for the UK to make connections with, and the Netherlands the worst. Germany's place at the top of the list is not surprising given its high demand for electricity and its high projected share of renewable electricity for 2030. Undoubtedly the mixture of available renewable technologies and their associated load factors will have a vast impact on the availability (depicted by F_1) in the proposed model. Furthermore, the quality of the results obtained will ultimately depend on the range and quality of the studies considered. By adopting extremes from over 50 studies to give a range of possibilities for supply through interconnection(s), the authors contest the data have been thoroughly tested.

An additional benefit of the tool is its capability to embed risk assessment add-ons such as @Risk (step 3) to facilitate consideration of energy uncertainties and risks. However, while step 3 provides a highly important risk assessment for 'surplus' exportable capacities within each country, it is not the only risk. Therefore, while this work moves considerably further in the right direction it does not yet tell specifically which country the UK should connect to. Further risk analysis would be required to do

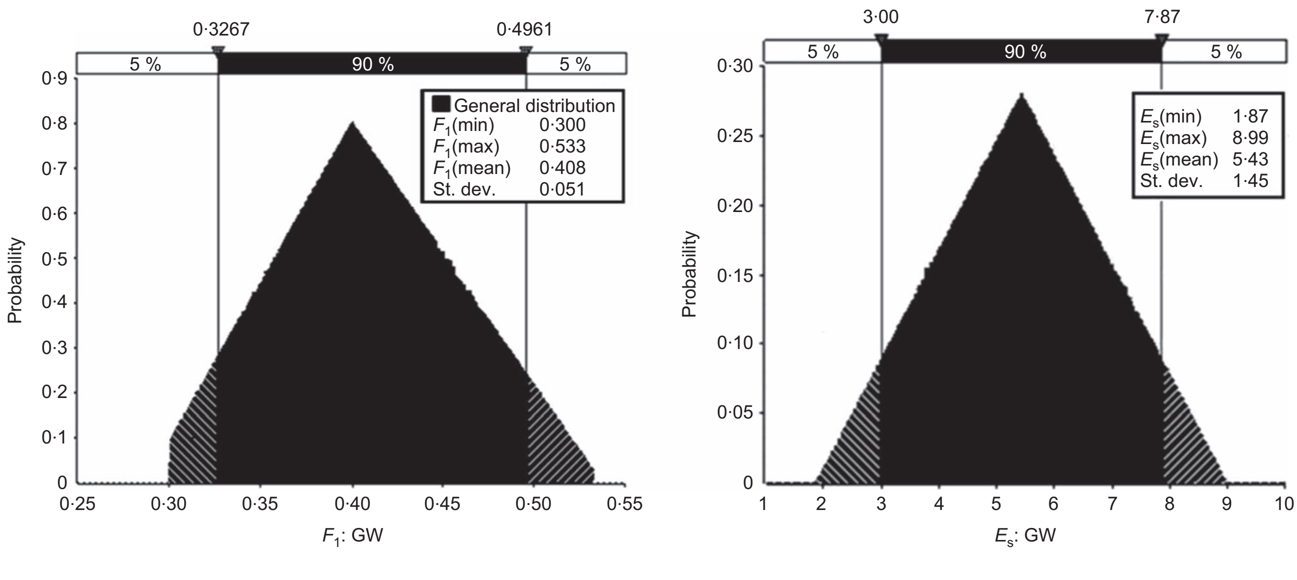

Figure 4. General and triangular probability distributions of F_1 and E_s, respectively, for Norway in 2030

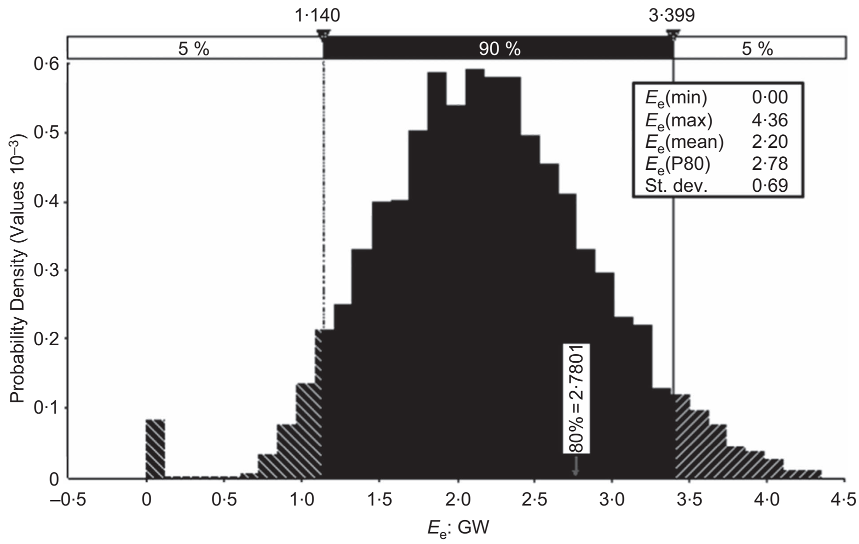

Figure 5. Risk analysis result for E_e (Norway–UK interconnection) in 2030

this, considering factors such as construction and operation. A contributing factor to the latter would include guarantees of origin (proof to a customer that a given share or quantity of energy was produced from renewable sources (European Commission, 2009)), without which the whole ethos of a supergrid would be undermined.

Ongoing research as part of this project is being used to supplement the risk assessment provided in this paper through a series of risk-based stakeholder interviews that will identify other risks that can be used within the proposed methodological approach. In light of the findings presented thus far, two additional key risks being considered in current work, which are equally influential to the viability of any supergrid, are now discussed. Namely, is a supergrid an economically viable option and can security of supply be assured?

	$E_{e(P80)}$: GW	Distance from London, UK: km
UK	5·475	—
Germany	10·971	918 (Berlin)
Spain	6·382	1254 (Madrid)
France	3·740	350 (Paris)
Sweden	3·007	1437 (Stockholm)
Norway	2·780	1129 (Oslo)
Ireland	0·898	467 (Dublin)
Belgium	0·662	312 (Brussels)
Denmark	0·638	941 (Copenhagen)
Netherlands	0·133	332 (Amsterdam)

Table 5. Projected $E_{e(P80)}$ capacities in 2030

4.1 Is a supergrid an economically viable option?

The economic viability of a supergrid is considered by many to be the primary driver of its success or failure (Black & Veatch, 2009; Denny *et al.*, 2010; DKM, 2003). Ultimately, such an evaluation requires cognisance of the cost of alternative supply technologies. Figure 6 shows 2013 costs for main technologies started in the UK in 2013 (Mott MacDonald, 2010). The least costly investment in 2013 was gas, followed by onshore wind and then nuclear. While gas has a relatively low capital cost investment, it is not a renewable source and inclusion of carbon dioxide emissions reduction (by means of CCS technology) increases costs significantly (CCC, 2011). A lack of inexpensive land near major population centres allied with the visual intrusion caused by large wind turbines has hindered the adoption of onshore wind technology (Bilgili *et al.*, 2011; CCC, 2011). It is thus not surprising that nuclear energy is claimed to be a vital part of a future, reliable, low carbon dioxide energy supply mix for the UK (CCC, 2011; Lynch, 2010).

However, as shown in Table 6, the cost of nuclear is significantly higher than the cost of a recently built interconnection between the UK and the Netherlands (BritNed, 2011). The cost implications of sourcing renewable sources in this way are a dominant influencing factor for decision makers when considering a supergrid. Cost is undoubtedly highly influenced by distance and it can be seen from Table 5 that the closeness of the Netherlands to the UK is an overriding cost factor even though it

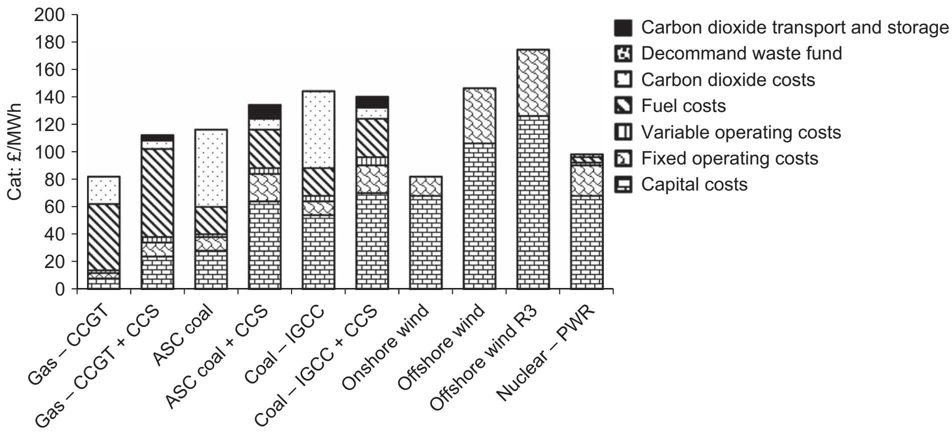

Figure 6. Levelised costs of main technologies for projects started in 2013 (data from Mott MacDonald (2010))

has low $E_{e(P80)}$ capacity in the current analysis. The same is not true of Germany, even though the $E_{e(P80)}$ was found to be more than 100 times greater. When considering distance and $E_{e(P80)}$ capacity (Table 5), France is a very sensible choice and therefore it is not surprising that a connection already exists and capacities are growing each year.

While the costs of technologies typically decrease over time (costs reduce through 'learning by doing') and through increasing economies of scale (Battaglini *et al.*, 2010), nuclear power is one of the few exceptions where costs have actually increased (Battaglini *et al.*, 2010; Cooper, 2009; Neij, 2008). Importing renewable electricity could therefore be an economically beneficial alternative for the UK. Such influences could be considerable in the identification of the most suitable partner country.

Williges *et al.* (2010) considered diversifying investment in renewable sources (e.g. concentrated solar power) in least-cost North African countries as a cost-effective solution. However, would a truly diversified renewables market lead to an overall improvement in the stability of electricity prices (Schaber *et al.*, 2012a) and would it allow for more or less penetrability? Would this be hindered by the over-integration of seemingly disparate market(s)? The argument is not straightforward and would require, at the very least, investment from two, but preferably multiple, countries. This recognises the fact that sources of renewable energy (e.g. marine technologies and wind farms (Hirschhausen, 2012)) may be located away from centres of demand, necessitating long-distance transmittance. This is something not readily apparent in Table 5 and yet it poses significant technical challenges and risks (Berdal Stromme, 1998; Georgiou *et al.*, 2011; Trieb, 2006), including energy losses and their associated economic costs (a function of cable distance, type (e.g. AC or DC) and location (i.e. underground, seabed or overhead)). The advantage of the Monte Carlo risk-based analysis presented here is that it can be used to identify which factors will most heavily influence the economic bottom line. Moreover, it will ultimately allow modelling of interdependencies between much broader ranges of input variables.

	Cost: £/kW
Nuclear plant (Thomas, 2010)	3200
BritNed interconnection (BritNed, 2011)	545

Table 6. Capital cost of nuclear plant against interconnection

One thing that cannot be ignored is the economic cost of carbon dioxide emissions (Table 2) and how renewable energy will be traded in the future. For example, Italy (not considered in this study) already plans to enhance its renewable targets by importing electricity produced from renewable sources outside of its borders (European Commission, 2009; Kovalyova, 2010). This would influence significantly the breakdown shown in Table 5.

4.2 Can security of supply be assured?

Ensuring security of future supplies poses an equally challenging prospect. When connecting to a single country it may be suggested that diversity of renewable supply sources (Table 4) is required in order to ensure security of supply. France, with five renewable technology sources, might once again be considered a suitable interconnection for the UK whereas Denmark, offering only wind and solar, (especially with the added influence of distance) may not. Undoubtedly a lower risk is posed in this respect through adoption of a large grid system where multiple supply paths exist in parallel (Hirschhausen, 2012; Van Hertem and Ghandhari, 2010). This would help overcome some of the intermittency issues related to availability when interconnecting with a single country; for example, while the renewables intermittency load factors for a specific technology (A_x) are assumed in the current analyses to be the same for all countries, the points at which they are available might differ significantly. This reduces risk considerably – the same philosophy underpins the adoption of any national grid system – because it is preferable to having multiple local dispersed grids. The supergrid just takes this concept to the next scale. It could be argued that the importation of renewable electricity by way of a supergrid provides an effective solution for reducing the dependency on long-distance imported fossil fuels from sometimes unstable countries while enhancing security of energy supply (Battaglini *et al.*, 2010; Hirschhausen, 2012). For example, in 2010, some 15·75% of the electricity consumed in the UK was sourced from Algeria, Egypt, Nigeria, Qatar and Yemen (DECC, 2011a). However, this also raises the question of whether importing electricity will ultimately bring a new kind of dependency and therefore pose new kinds of threats to supply security (e.g. Zeller, 2009). Battaglini *et al.* (2010), for example, recognise the importance of selecting a 'good government' (e.g. Norway in our analysis) to guarantee that imports are secure and beneficial for both sides: governance issues along with clear policy guidance are paramount to success (or failure).

Renewable energy generation output (e.g. wind, hydro and solar) is naturally variable and unpredictable, and balancing these issues is seen as one of the main requirements for the seamless integration of renewable energy supply sources (Van Hertem and Ghandhari, 2010). In addition, renewable electricity, once generated, needs to be used because it is technically inefficient and costly to store (Achenbakh, 2010; Koponen *et al.*, 2008). It could be argued that security of supply is improved (i.e. intermittency becomes less of an issue) within a supergrid network because of the geographical dispersion of supply sources (Battaglini *et al.*, 2010; ECCC, 2011b; Schaber *et al.*, 2012b). This allows for the disassociation of localised weather systems (Van Hertem and Ghandhari, 2010). For example, in Europe, wind energy from the UK can be partially balanced with solar energy from Spain or North Africa (e.g. Sahara desert) or hydro power from Scandinavia or the Alps. In so doing, the supergrid reduces the requirement for back-up generation (Aboumahboub *et al.*, 2010; ECCC, 2011b).

Security of supply issues is further reduced due to the intricacies of time zoning. For instance, there is at least 1 hour difference between the UK and other North Sea bordering countries and this will facilitate offsetting peak demand requirements in each country during the day (Van Hertem and Ghandhari, 2010). This argument is enhanced further when considering the differences in lifestyles and various end uses for electricity around the EU, bringing added flexibility and improved security to the grid during peak hours.

Notwithstanding these advantages it should be recognised that a common mode failure, should it occur, would impact the entire DC supergrid and could feasibly stop all power transfers, potentially leading to generation imbalances (Hirschhausen, 2012; Van Hertem and Ghandhari, 2010).

5. Conclusion

A three-stage methodological framework that can be used to assess interconnection capacities and risks associated with a UK pan-European supergrid has been described. Drawing on an extensive database of existing energy scenario sets, a newly developed Excel-based tool was used to project supply/demand capacities for the UK and nine European countries. By using generated surplus capacities for renewable electricity, risk-based 80th percentile (P80) estimates for interconnections were assigned using @Risk software. Based on the assumptions made, it was found that the greatest P80 interconnection capacity (5·5 GW) for 2030 was from a UK–Germany link. It is proposed that, with further stakeholder engagement, the developed methodological framework and associated tool will be invaluable for decision makers within the energy sector.

Acknowledgements

This study was funded by the University of Birmingham by means of a post-graduate teaching assistantship to Mehran Eskandari Torbaghan and by a grant from the Engineering and Physical Sciences Research Council (EPSRC) under the current Liveable Cities (EP/J017698) programme, which funded Dr Dexter Hunt.

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